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Nakawo, N.; Frederking, R. M. W.

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SOMMAIRE

Une façon d'augmenter l'épaisseur d'une couche de glace consiste à la recouvrir d'eau. La glace est constituée de couches successives d'eau de mer gelée. La salinité de la glace ainsi formée joue un rôle très important dans les caractéristiques mécaniques de cette glace.

On a procédé à des observations précises lors de la construction d'une plate-forme en glace artificielle. La salinité observée était de l'ordre de 20 ‰, donc moindre que celle de l'eau de mer qui était à l'origine de la formation de la glace, soit ~30 ‰. Presque la moitié de la perte en sel avait eu lieu pendant la période de gel de la couche ; l'autre moitié au cours de la formation des autres couches successives. Les auteurs concluent qu'il y a une baisse de la salinité dans le sens horizontal et dans le sens vertical pendant la construction de la plate-forme après avoir mesuré avec précision la salinité, des couches minces et le déplacement des teintures.

THE SALINITY OF ARTIFICIAL BUILT-UP ICE MADE BY SUCCESSIVE FLOODINGS OF SEA WATER

M. Nakawo*
Research Associate

R. Frederking
Research Officer

Division of Building Research
National Research Council of Canada
Ottawa, Ontario, Canada

Canada

ABSTRACT

One method of thickening an ice sheet is "free flooding": ice is built up by successive flooding and freezing of sea water layers. The salinity of the built-up ice is of great interest because it plays an important role in establishing mechanical properties.

Detailed observations on salinity of flooded water and built-up ice were carried out during construction of an ice platform. Ice salinity was generally about 20‰ which is significantly lower than the salinity of the original sea water (~30‰). Almost half of the "lost salts" disappeared during the freezing period of a layer; the remainder were lost during subsequent floodings. Detailed salinity, thin section and dye migration measurements were used to postulate processes of horizontal as well as vertical desalination during construction of the ice platform.

* Present address: Applied Physics Section, Faculty of Engineering, Hokkaido University, Sapporo, Japan 060

Floating ice platforms have provided a very successful means for carrying out exploratory drilling in the Canadian arctic islands [1]. Since the first ice platform was constructed and used for drilling in 1974 the trend has been toward increasing rig loads and lengthened drilling periods. Consequently, efforts have been devoted to developing an improved basis for ice platform design [2] as well as platform construction [3].

The technique used in constructing an ice platform is "free flooding", i.e., ice built up in layers by successive flooding and freezing of sea water pumped from beneath the ice cover. Grain structure and salinity of built-up ice plays an important role in establishing its mechanical properties. Observations have shown that the salinity of the built-up ice is significantly lower than that of the original sea water. An explanation of this desalination process is of considerable interest. This paper presents field data on spatial and temporal distribution of salinity in built-up ice and discusses processes that control these distributions.

Description of Observation Site

The field observations were made 14 to 20 January 1979, at Panarctic's Desbarates B-73 well site which was located 76° 42' and 105° 57' W, northeast of Melville Island. Two platforms were constructed at the site: one for the drilling operation and the other for the drilling of a relief well if necessary. The actual measurement program was carried out on the relief platform.

Two pumps located near the centre of the platform lift sea water from beneath the ice and discharge it on the surface. Average sea water salinity was 30.8 ±0.6‰. Distribution of the water was controlled by periodic adjustment of the discharge direction of the pump nozzle. The resulting platform was elliptical in shape with maximum and minimum diameters of approximately 200 m and 100 m respectively. There was no confinement to the water flow and "free flooding" resulted in a platform with maximum thickness at the centre, tapering to the natural ice thickness at the edge, i.e., the platform surface sloped slightly downwards from the centre (inclination about 0.4°).

At the time of the field program the total ice thickness of the platform was about 3 m at the centre and 1.8 m at the edge (natural ice thickness). The duration of a single flood was 0.5 to 1.0 h, with a resulting layer thickness of 10 to 20 mm. Flooding frequency was once every 3 to 5 h. Altogether 31 floods were made during the observation period for a total ice build-up of almost 0.5 m.

Detailed observations were made along a radial line running outward about 60 m from one of the pumps. This line corresponded to one of the short axes of the platform so the observation area covered a representative section extending from the centre to the edge. The field observations included measurements of salinity of the sea water and built-up ice and also temperature in the built-up ice. A core was recovered and returned to the laboratory for further salinity measurements and analysis of grain structure.

Results

Salinity of the surface layer was measured at a number of positions in the observation area several times during the observation period. The surface layer samples were recovered shortly before the next flood. Horizontal distribution of the surface layer salinity is shown in part (b) of Figure 1. Note that up to 30 m, surface layer

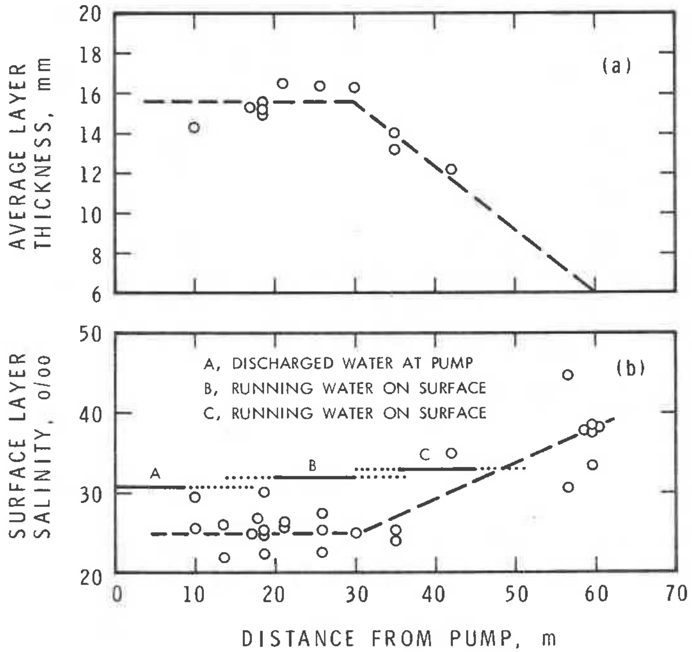

Figure 1

Variations of layer thickness (a) and salinity (b) with increasing distance from pump

salinity is about 25‰ but beyond 30 m it increased to about 35‰. This figure also shows the salinities of pump discharge water and water running on the surface during flooding. These data show an increase in salinity with increasing distance from the pump. Part (a) of Figure 1 presents average layer thickness as determined by measuring total ice build-up over the observation period and dividing by the number of floods in that period (31). Each flood did not completely cover the area beyond 30 m, which accounts for the reduction in average layer thickness beyond 30 m.

From a core taken 18.5 m from the pump, vertical thin sections were made and a vertical salinity profile established (Figure 2). Each salinity value represents the average of that particular layer. The surface salinity of the vertical core (25‰) corresponds well with the average surface salinities shown in Figure 1. The vertical

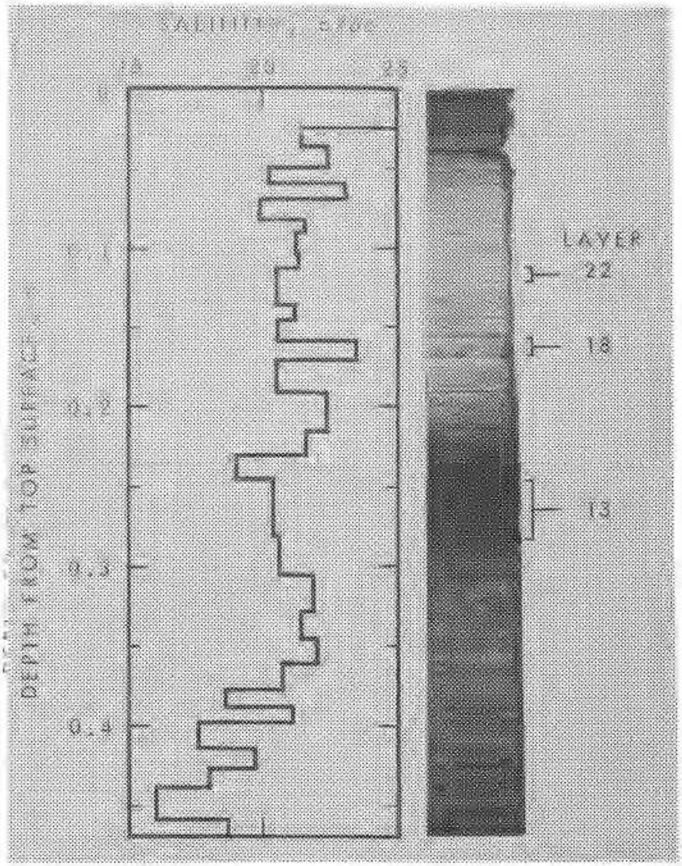

Figure 2

Vertical salinity profile obtained for a core sample taken 1979-01-20 at a distance of 18.5 m from pump

profile shows that to a depth of 0.4 m salinity was in the range of 20 to 22‰. Below 0.4 m, there was a further decrease in salinity. The boundaries of the individual flood layers can be quite clearly distinguished as dark lines in the thin sections.

An enlargement of the profile at a depth of 0.28 m (reference level) is shown in Figure 3. The boundaries as shown in the thin section are indicated by the dashed lines. The salinity profiles within a layer show a characteristic "double S" distribution, i.e., salinity is high on the layer boundary, decreases to a minimum at the quarter point in the layer, increases to a peak at the mid-point in the layer, decreases to another minimum at the three-quarter point, and finally to another maximum on the boundary. Grain structure also shows a characteristic pattern: fine-grained granular ice on the boundaries, bands of elongated grains at the quarter and three-quarter points in the layer, and a very irregular band is in the middle of the layer.

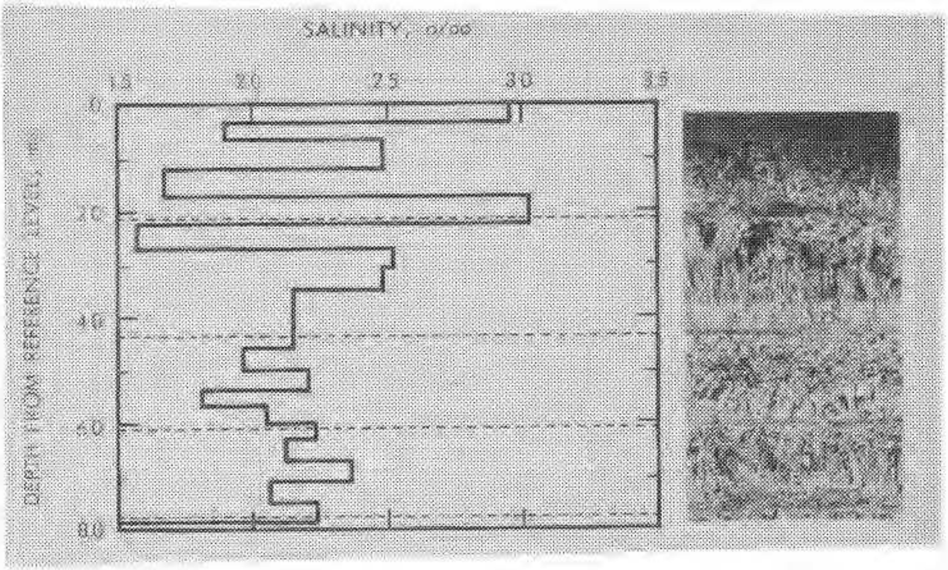

Figure 3 Detailed salinity profile for four flooded layers in the core sample

Measurements were also made of temperature and salinity changes with time in the upper layers of the built-up ice. Part (a) of Figure 4 indicates time variations of temperature at different depths in the built-up ice during several flooding and freezing cycles. The temperature curves labelled Layers A, B and C were measured within the most recently flooded layer. At the beginning of a flood these temperatures were high as the relatively warm (-2°C) sea water was discharged onto the ice surface. A rapid decrease in temperature followed the completion of the flooding. At greater depths in the ice, temperature fluctuations were attenuated and a phase shift was evident. Below a depth of about 200 mm ice temperature did not respond to individual floodings.

Part (b) of Figure 4 presents results of periodic salinity measurements of particular layers during several flooding and freezing cycles. In the case of each flood the first point was the salinity of the sea water. Subsequent samplings showed a gradual decrease in salinity to about 25‰ at the end of the freezing period. During successive floodings (Layers B and C) there was a further decrease in the salinity of the underlying ice (Layer A) to 20 to 22‰ (the same salinity as found at intermediate depth in the vertical profile (Figure 2)).

In addition to the salinity, temperature and thin section observations, a dye experiment (using Rhodamine B) was carried out to visually trace the directions of

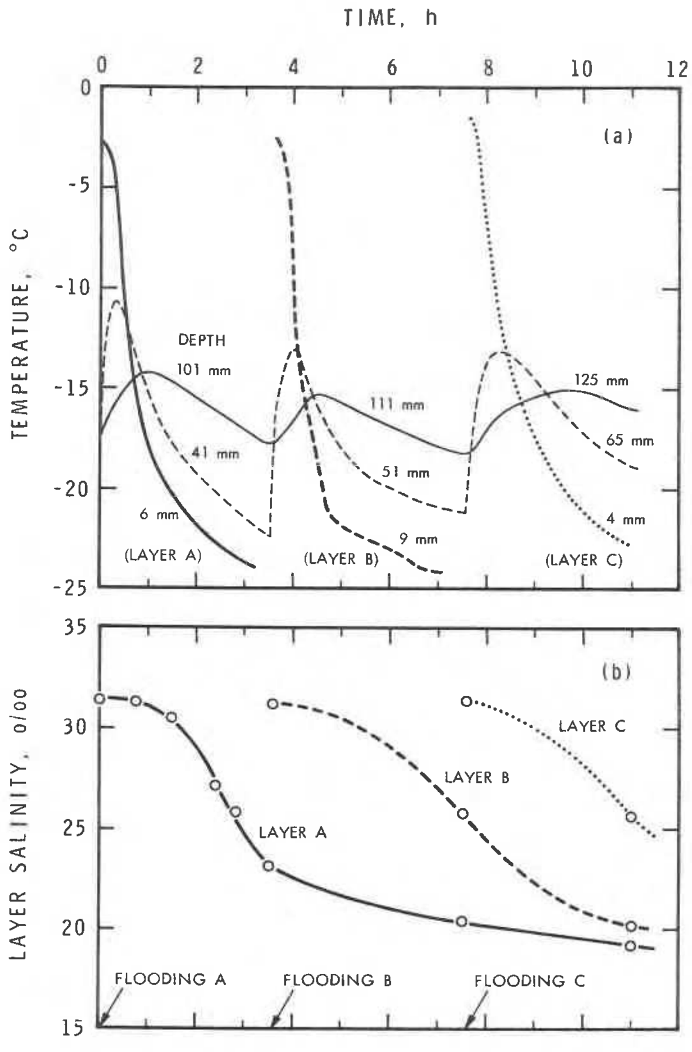

Figure 4

Time variation of temperature (a) and salinity (b) for three flooding cycles measured 1979-01-18 at a distance of 18.5 m from pump

brine movements. The results of the experiment are illustrated in Figure 5. After the current surface layer, α, had frozen, a trench, β, was cut normal to the water flow direction. The trench was then filled with dyed water and allowed to freeze. The next flooding produced layer γ. After layer γ had frozen, a vertical section was cut across the trench. Figure 5 shows that the dyed area extended horizontally, in the water flow direction, and downward, indicating that there was brine movements in these directions.

Another dye experiment was carried out in the area where the vertical core was recovered (Figure 2). In this case dye was mixed with the water in layer 22. Two

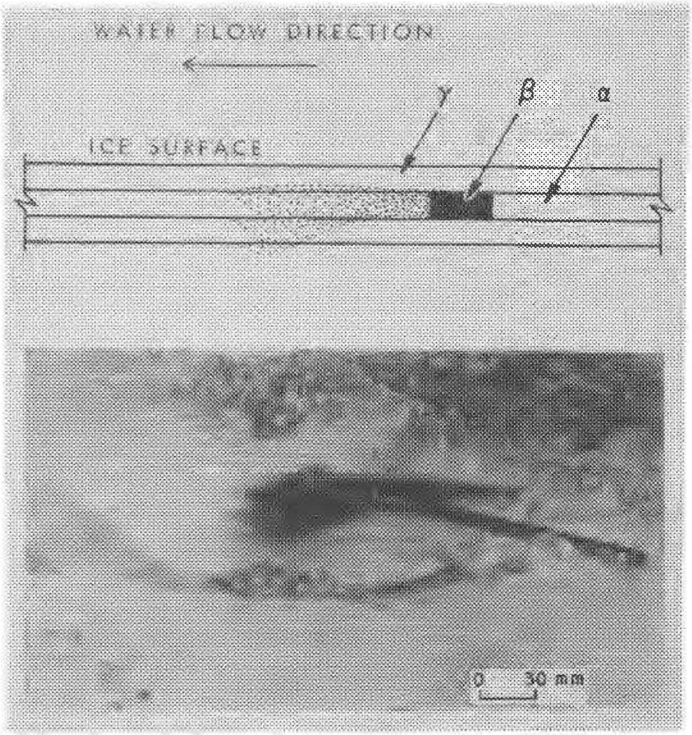

Figure 5

Vertical section schematic and photograph of dye migration experiment

days later, when the core was recovered, the dyed zone extended downward from layer 22 to layer 18. When another core was recovered two months later, the dyed zone extended further downward to layer 13. By this time, however, the colour intensity of the dye had greatly reduced. Also noteworthy was the absence of any apparent upward migration of dye.

Discussion

The dye experiments demonstrated, if only in a qualitative fashion, that brine moves vertically downward and horizontally in the built-up ice. It is possible, however, to make some first order quantitative estimates of these brine movements. The results presented in Figure 1 showed an increase in salinity with distance from the pump. Combining the salinity data with the average layer thickness, a mass balance was carried out on the salt in a sector of radius 60 m from the pump and arc 1 radian (see Table I for results). Area 1 comprises the zone from the pump out to 30 m; area 2 the zone from 30 m to the position where the average surface layer salinity is equal to the sea water (43.5 m); and area 3 the zone from 43.5 m to 60 m. Row 1 of the table gives the mass of salt in each area for an equivalent layer of sea water; row 2 the actual mass of salt in the surface layer of ice (calculated from measured

Table I. Salt content distribution in an average layer

		Area 1	Area 2	Area 3	Total
Row 1	Salt in Water, kg	398	374	412	1184
Row 2	Salt in Ice, kg	323	340	457	1120
Row 3	Difference, kg	-75	-34	+45	-64

salinity and layer thickness); and row 3 the differences. Area 1 experienced about a 20% loss of salt (desalination), area 2 about a 10% decrease and area 3 about a 10% gain in salt. Over the three areas there was a net loss of 5%. From these numbers there is evidence of a horizontal redistribution of salt, decrease in areas 1 and 2 and increase in area 3, as well as an over-all loss of 5% from the surface layer due to vertical drainage. In area 1 during the initial freezing period, desalination was equally the result of vertical and horizontal brine movement. To quantify this breakdown more accurately, experimental measurements of permeability of built-up ice would be needed. Visual evidence of horizontal brine movement was indicated by the observation of high salinity brine seeping from the outer edge of the top flooded layer at the end of the freezing period. Similar observed indications of horizontal brine movements were noted during flooding experiments at Point Barrow [4]. The driving force for this movement could be internal pressure generated within a layer during freezing. The results in Table I were for the initial freezing of the surface layer. If an average salinity for area 1 corresponding to successive floods (20‰) were used, the proportion of desalination due to vertical brine drainage would increase to 10%.

As shown in Figure 2 the salinity of the built-up ice below the surface layers is about 20‰ which is supported by the observations presented in Figure 4. It appears that after the initial desalination (down to 20‰) further vertical brine movements are by a displacement process, i.e., salinity over the depth of 0.05 to 0.4 m does not change. For depths below 0.4 m the decrease in salinity can be attributed to the effects of temperature and temperature gradient in promoting brine movements [5].

The detailed salinity profile and thin section illustrating grain structure (Figure 3) can be explained as follows. The high salinity and fine grained structure of the ice at the top and bottom of each layer would result from rapid freezing when the sea water comes in contact with the cold ice surface and air. Subsequent ice growth would occur from both the top and bottom of the layer, but at a slower rate which would allow more of the brine to be ejected from this part of the layer. Here one would expect a lower salinity and a larger grained columnar structure. The centre of the layer, the last part to freeze, would have a higher salinity and a more irregular grain structure.

Conclusions

An analysis of the results suggests that there are three stages of desalination. In the first stage, freezing period of the top layer, salinity is reduced from 31‰ to 25‰ as a result of vertical and horizontal brine movements. The second stage sees a further reduction in salinity to 20‰ during the next two floods. The salinity remains approximately constant at this value until such depth is reached where the ice temperature is higher than -15°C. During construction the temperature reaches this level at a depth of about 0.5 m [3]. This leads to the third stage of desalination which is caused by warming of the ice. An extension of the third stage of desalination occurs in the spring with seasonal warming of the ice cover.

In addition to providing information on the desalination processes, the results given in this paper show the difficulties that would be experienced in trying to simulate in the laboratory the open system process for building up the ice that occurs in the field.

Acknowledgements

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Discussion by Andrew Assur, USA CRREL

The detailed study of salinity distribution after flooding is certainly a welcome contribution. The desalination is quite modest, i.e. the resulting salinity is still quite high. At low temperatures (approx. -25°C) this would not matter, but under warmer conditions a gradual deterioration could take place. What are the observations? What are the salinity changes after several months?

Reply to discussion

Some observations carried out in early May, when ice temperatures were approaching -10°C, still did not show signs of deterioration or further significant desalination. By late June, however, there were obvious signs of deterioration and ice salinities were of the order of 5‰.